

FINAL REPORT

Determining the Atmospheric Structure and Dynamics
of the FK Comae Star HD32918 P-11

Principal Investigator R.D. Robinson
Institution: Computer Sciences Corporation
Contract Number: S-97225-E

1. Primary Objectives of the Project:

The study was originally planned to be a coordinated campaign between the IUE and the Australia Telescope to study the dynamics of the rapidly rotating K giant HD32918, which has been classified as an FK Comae type object. After being awarded the time, however, the ROSAT Wide Field Camera all sky survey discovered the existence of pronounced EUVE radiation from the K0 dwarf HD197890. This star was subsequently found to have a rotation velocity in excess of 170 km s^{-1} , nearly 50% greater than previously measured on a single (i.e. non-binary) cool star. Since magnetic field generation in cool dwarfs is thought to be related to rotational velocity, this star represented a sample at the extreme limits of stellar activity. For this reason we proposed to change the target of this proposal, and the request was granted. The observations consisted of time sequences of low resolution LWP and SWP exposures which were intended to examine the strengths and time variations of the UV emission lines and continuum. The objects were coordinated with radio observations from the Australia Telescope. It was then planned to compare these observations with those of a range of other rapidly rotating stars found in the IUE archives and in the literature.

2. Results of the Study:

The observations have been obtained and were completely analyzed. The analysis showed that the star had pronounced emission lines, whose surface flux was greater than any other K dwarf and comparable in strength to those in active stars such as W UMa contact binaries, RS CVn binaries and dMe flare stars. A variation was found in the LWP continuum which appeared to be phase related, suggesting the existence of surface inhomogeneities. The line emission did not show a clear rotational modulation, but did occasionally show evidence of rapid variations which may have been caused by stellar flares. The source was also found to be a strong quiescent radio source at both 4.8 and 8.4 GHz which did not show any evidence of variability during the 4 day observing session, but did show a significant difference in flux from data taken approximately 1 month earlier. Comparing the observations with those from other rapidly rotating K stars in the IUE archive showed that it lay on a smooth line relating line strength (as measured by the emission line flux) and rotation rate. The same conclusion could be

drawn concerning its radio emission. However, despite the high levels of 'quiescent' flux, HD197890 showed no evidence for the large flare-like radio events which are commonly seen in other, more slowly rotating K dwarfs such as AB Dor and PZ Tel.

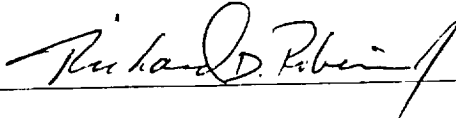
To better understand the characteristics of this and similar stars we have started on a theoretical investigation attempting to apply non-LTE radiative transfer techniques to the empirical modeling of the stellar atmosphere. This investigation is still in progress and will be completed with other funding sources.

3. Publications:

The results of the study were published in the paper:

"Ultraviolet and radio observations of the young, rapidly rotating K0 dwarf star HD197890", Robinson, Carpenter, Slee, Nelson and Stewart, MNRAS, 267, 918 (1994).

A copy of this paper is appended.

 03/23/95

Signature of Principal Investigator Date

Ultraviolet and radio observations of the young, rapidly rotating K0 dwarf star HD 197890

R. D. Robinson,¹ K. G. Carpenter,² O. B. Slee,³ G. J. Nelson³ and R. T. Stewart³

¹*Astronomy Programs, Computer Sciences Corporation, Code 681/CSC NASA–Goddard Space Flight Center, Greenbelt, MD 20771, USA*

²*Laboratory for Astronomy and Solar Physics, Code 681, NASA–Goddard Space Flight Center, Greenbelt MD 20771, USA*

³*Australia Telescope National Facility, CSIRO, PO Box 76, Epping, NSW 2121, Australia*

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ABSTRACT

We present the results of UV observations taken with the *International Ultraviolet Explorer* (IUE) satellite and microwave observations obtained with the Australia Telescope during an observing campaign of the rapidly rotating K0 dwarf star HD 197890, nicknamed ‘Speedy Mic’. This star was recently recognized as a powerful, transient EUV source by the *ROSAT* WFC, and subsequent investigation showed it to be a ZAMS or possibly a PMS dwarf which may be a member of the Local Association. Our observations show it to have strong, variable UV emission lines near the ‘saturation’ levels. The radio observations show a level of ‘quiescent’ emission consistent with other rapidly rotating stars, but there is no evidence for the large flux variations that normally characterize the time history of such objects.

Key words: stars: activity – stars: individual: HD 197890 – stars: late-type – stars: rotation – radio continuum: stars – ultraviolet: stars.

1 INTRODUCTION

On 1990 October 17, the *ROSAT* Wide Field Camera (WFC) all-sky survey detected a strong transient flux increase in a source subsequently identified as the K0V star HD 197890 (see Bromage et al. 1992). This transient reached a peak flux of at least 20 times the quiescent level (the star was not detected in quiescence), and represented a total energy release of $> 10^{33}$ erg within the *ROSAT* S2 wavelength range. Subsequent ground-based observations showed a rotational $V \sin i$ of 170 ± 20 km s⁻¹ (Anders et al. 1993) and no evidence of any non-random radial velocity variations greater than 2 km s⁻¹, indicating a probable single star (Bromage et al. 1992). The star also shows a periodic photometric variation of $\Delta V = 0.2$ with a period of 7 ± 1 h (Anders et al. 1993). This, combined with the rotational velocity, indicates a value of $R \sin i$ of about $0.98 \pm 0.14 R_{\odot}$, which is larger than expected for a normal K dwarf and suggests that the star is still collapsing toward the main sequence and has not yet had the opportunity of slowing to the more usual rotational velocity of < 10 km s⁻¹. Other evidence for youth is the strong Li $\lambda 6708$ -Å line (220 ± 50 mÅ), since lithium is quickly destroyed in stars with strong convective envelopes (e.g. Duncan 1981).

Bromage et al. (1992) suggested that HD 197890 was a member of the Pleiades group, similar to AB Dor, PZ Tel and V343 Nor (Innis, Thompson & Coates 1986), which

have ages of about 70 Myr. While this may be true, Anders et al. (1993) have pointed out that this star has a net proper motion which is directed approximately 20° away from the convergent point of the Pleiades. Anders et al. also present evidence suggesting that HD 197890 may be much younger than stars in the Pleiades (with an age of about 10⁷ yr) and may, in fact, be a pre-main-sequence (PMS) object. Even if HD 197890 is not a member of the Pleiades association, however, there is strong evidence that it shares many of the physical properties of these other nearby, rapidly rotating single stars. These stars are identical to the rapidly rotating K stars found in young open clusters such as the α Per cluster and the Pleiades (see, for example, Stauffer 1991), but have the advantage of being much closer so that their behaviour can be studied in detail. For example, Jeffries (1993) has recently reported the existence of a strongly variable H α feature on HD 197890. This line sometimes goes into emission and also shows evidence for transient absorption features similar to those seen on AB Dor (Collier Cameron & Robinson 1989), which are probably caused by clouds of cool material trapped in large magnetic loops. Such clouds can possess a significant amount of angular momentum, and it has been suggested that their formation and subsequent expulsion is a mechanism whereby a star sheds angular momentum (Collier Cameron & Robinson 1989). Also, since the generation of magnetic activity in cool stars depends strongly on the stellar rotation rate through a

dynamo process (e.g. Parker 1979), the activity in these objects is pronounced. These stars therefore present an opportunity for studying magnetically related activity such as flares, starspots, chromospheres and coronae at extreme levels without the complication of a binary companion.

In this paper we present the results of an observing campaign designed to determine the properties of HD 197890 in the UV and radio regions.

2 OBSERVATIONS AND DATA REDUCTION

The *IUE* observing campaign was carried out on 1992 April 10–14 and consisted of four US 1 shifts. An observing log is presented in Table 1. The first three days consisted of sequences of interleaved LWP and SWP spectra. The SWP exposure times required to obtain a reasonable spectrum were long, averaging 3 h, and so represent a substantial amount of phase smearing. The LWP exposures were shorter, averaging 25 min each. To increase the number of LWP samples we took two spectra per frame, with the star positioned near the edges of the aperture. On the final day, we concentrated exclusively on LWP exposures, again taking two exposures per frame. This was designed to detect any rotational modulation of the Mg II fluxes that might be associated with the periodic optical variations.

The LWP and SWP spectra were extracted from processed line-by-line files using a normal Gaussian-weighted extraction. The background in the SWP spectra was determined by a linear least-squares fit to regions of the spectrum

with no known emission lines. After subtracting the background, the emission-line fluxes were determined by direct integration. Extraction of the Mg II fluxes from the low-resolution LWP spectra was more of a problem because of the strong, broad absorption component associated with the lines, as pointed out by Hartmann et al. (1984). In measuring the lines, we integrated over the wavelength range from 2785 to 2815 Å and obtained two numbers: the first is the total integrated flux, f_{gross} , while the second is the integrated flux above an average 'continuum' level measured near 2785 and 2815 Å. The actual emission-line flux lies between these two values. To determine the conversion we used high- and low-resolution *IUE* archive spectra of the active K dwarf AB Dor. The Mg II lines were resolved in the high-resolution spectra and the fluxes, F_h and F_k , were extracted by doing a least-squares fit to the absorption features and then integrating the emission core above the fitted line. The net and gross fluxes were then determined from low-resolution spectra, which were nearly contemporaneous with the high-resolution observations, and a relation was determined between the actual emission-line flux from the Mg II h and k lines, F_{hk} , and the measured low-resolution fluxes. The procedure was repeated for all available high/low-resolution observations taken of AB Dor, as well as observations of other stars of similar spectral type. The results were consistent, and had the form

$$F_{hk} = 0.35 F_{\text{gross}} + 0.65 F_{\text{net}}.$$

The individual SWP spectra were very noisy, with a signal-to-noise ratio typically in the range 5–7 at the peak of the

Table 1. *IUE* observing log.

Image	Exposure Number	Dispersion	Exposure Time (min)	Date Taken	Start Time (UT)	Phase ¹
LWP22781	1	low	20	10-Apr-1992	10:56:10	0.00
LWP22781	2	low	20	"	11:21:31	0.07
SWP44372	1	low	120	"	11:56:17	0.14
LWP22782	1	low	25	"	14:01:32	0.44
LWP22782	2	low	16	"	14:29:16	0.51
SWP44373	1	low	120	"	14:49:23	0.56
LWP22793	1	low	30	12-Apr-1992	09:46:18	0.70
SWP44383	1	low	180	"	10:27:16	0.80
LWP22794	1	low	25	"	13:35:52	0.24
SWP44384	1	low	170	"	14:06:23	0.31
LWP22803	1	low	25	13-Apr-1992	09:47:12	0.13
SWP44391	1	low	180	"	10:16:30	0.20
LWP22804	1	low	25	"	13:30:35	0.66
SWP44392	1	low	165	"	14:04:28	0.74
LWP22811	1	low	25	14-Apr-1992	09:35:27	0.53
LWP22811	2	low	25	"	10:09:44	0.60
LWP22812	1	low	25	"	11:14:15	0.76
LWP22812	2	low	25	"	11:48:02	0.84
LWP22813	1	low	25	"	12:49:33	0.99
LWP22813	2	low	25	"	13:23:34	0.07
LWP22814	1	low	25	"	14:26:15	0.21
LWP22814	2	low	25	"	15:00:09	0.30
LWP22815	1	low	25	"	15:58:19	0.44
LWP22815	2	low	25	"	16:28:43	0.51

¹Arbitrary zero-point using a period of 7 h.

prominent emission lines. To enhance the spectrum for detailed analysis, we combined the individual spectra into a single 'average' spectrum using a weighted mean technique similar to the one described by Ayres et al. (1986). Briefly, this involved first cross-correlating the individual spectra on the strong C IV feature to ensure a common wavelength scale and then determining the weighted mean flux at each wavelength point. All points with a non-zero data quality (eps) flag or a flux deviating by more than 3σ from the average (provided that there were three or more spectra) were given a reduced weight when taking the mean. This technique will not remove the fixed pattern gain variations on the detector photocathode, since all the observations were taken at essentially the same position along the slit. It does, however, effectively reduce the effects of Poisson noise and cosmic ray events. The results of this analysis for both the LWP and SWP observations are presented in Figs 1 and 2, where the spectra have been compared with those of the nearly identical, though somewhat slower rotating, star AB Dor.

The radio data were taken using the compact array of the Australia Telescope. Using the dual-feed system on each of the six antennas, we were able to observe simultaneously at 4.8 and 8.4 GHz and to record the four Stokes parameters. The synthesized beamwidths at 4.8 and 8.4 GHz were about 2 and 1 arcsec, respectively. The data were calibrated using the unresolved source PKS 2106-413, located about 6° from the centre of our field. The usual editing, mapping and cleaning procedures in the AIPS software were followed to produce 512×512 pixel maps. In Fig. 3 we show the 4.8-GHz map made by concentrating the data from two 12-h observing sessions on 1992 April 10/11 and April 12/13. Three sources of comparable magnitude were found in the

field. Source A is within 1 arcsec of the position of HD 197890. Source B is in an empty optical field and source C coincides with an 18.0-mag elliptical galaxy.

3 RESULTS

Fig. 1 shows the results of a direct comparison of the co-added LWP spectrum of HD 197840 with a similar spectrum of AB Dor, determined by co-adding three spectra obtained from the *IUE* archives. The AB Dor fluxes have been reduced by a factor of 17 to match the continuum levels. Note that the general features of the two spectra match extremely well, confirming the assertion that the two stars are of similar spectral type. The continuum intensity ratio of 17, however, is inconsistent with a measured difference of 10 in the Johnson V -band intensities, implying that HD 197890 may be of later spectral type than AB Dor, as suggested by Anders et al. (1993).

To check for UV continuum variations which might be associated with the photometric variations seen in the optical, we integrated the individual LWP spectra between 2600 and 3000 Å, excluding the region between 2780 and 2810 Å which was influenced by the Mg II resonance lines. The results are shown in Fig. 4(b) and listed in Table 2. The phases were calculated using an arbitrary zero-point (the start of the first observation) and a rotational period of 7 h, as reported by Anders et al. (1993). The continuous time sequence (taken on April 14 and shown as open squares) indicates a rotational modulation at the 5 per cent level, which is confirmed somewhat by observations on other days. The large uncertainty in the rotational period, however, makes these comparisons uncertain.

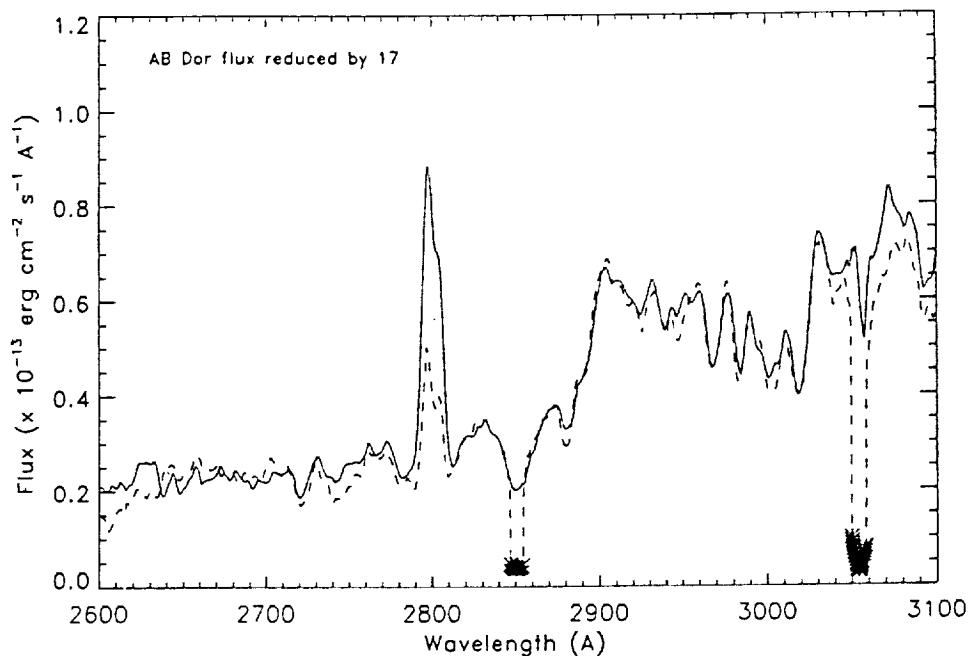


Figure 1. Comparison of the Mg II region of HD 197890 (solid line) with that of the rapidly rotating K0 dwarf AB Dor (dashed line). The HD 197890 spectrum results from the co-addition of 18 LWP exposures taken during four observing shifts. The AB Dor spectrum represents the co-addition of three LWP spectra taken in 1990. The flux of the AB Dor spectrum has been reduced by a factor of 17. The crosses indicate questionable spectral points.

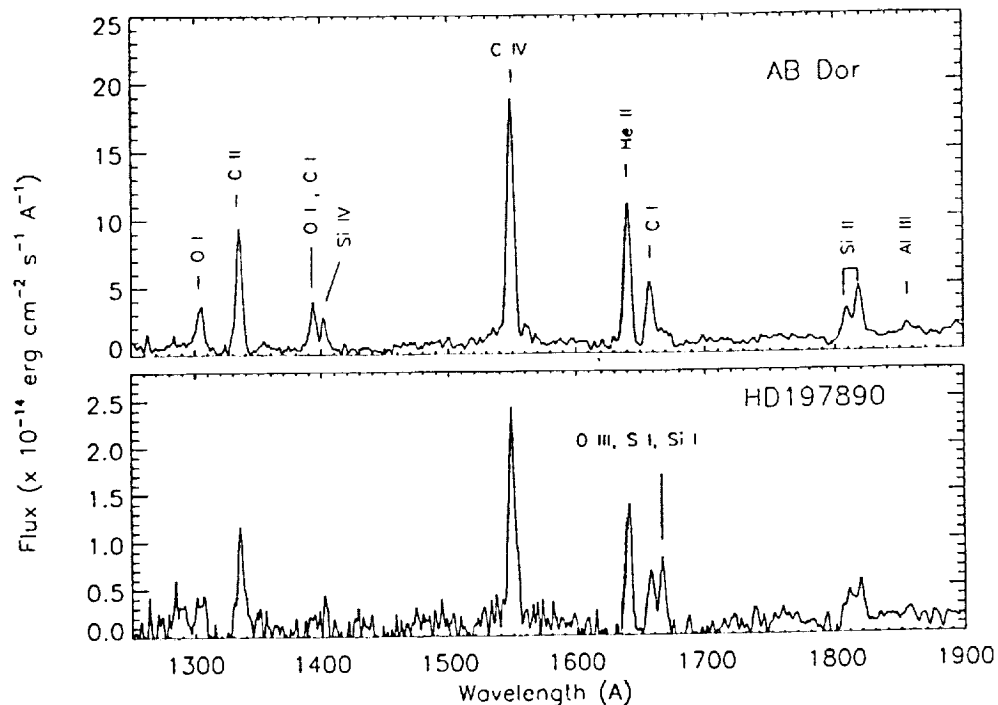


Figure 2. Comparison of the far-UV spectra of HD 197890 and AB Dor. The HD 197890 spectrum represents a co-addition of six SWP exposures taken during our observing run, while the AB Dor spectrum is a co-addition of 23 SWP spectra taken during observing sessions in 1983, 1988 and 1990.

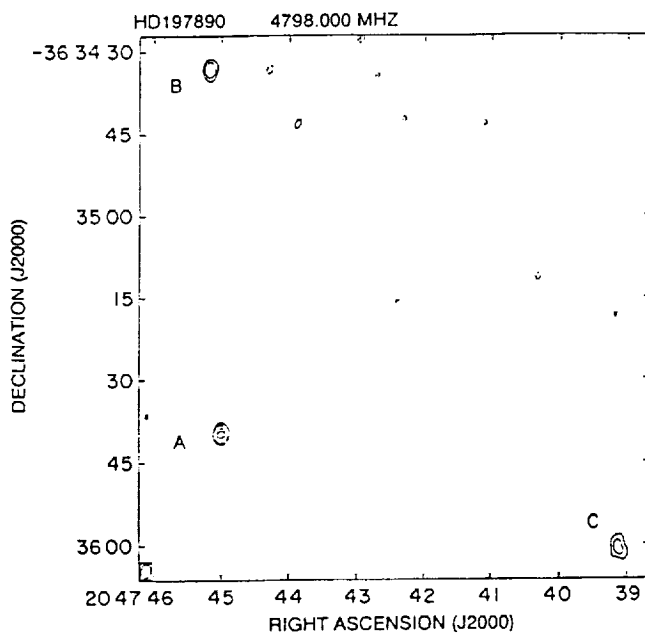


Figure 3. A cleaned 4.8-GHz map of the area around HD 197890, made by concatenating the data from two 12-h observations in 1992 April. The peak flux density is 2.0 mJy and the contour levels are -15, 15, 30, 60 and 80 per cent of the peak. The rms noise level over the map is 87 μ Jy per beam.

In Fig. 4(a) we show the behaviour of the integrated Mg II fluxes. For most of the spectra, the measured Mg II flux was near the mean value, with variations consistent with measurement errors. In four cases, however, the deviations

were more extreme, with two spectra showing enhancements and two showing depressions. In none of these cases was the continuum intensity significantly different from that expected, and it is probable that these deviations represent true transient activity.

Table 3 presents the measured fluxes for prominent lines in the six SWP spectra obtained in this programme. There is no indication of phase-related variations, though this may not be surprising in the light of the strong phase smearing resulting from the long exposure times (one exposure was about 0.25 of an orbit). Note that, while the C IV fluxes remain relatively constant, other relatively strong lines such as C II (1335 Å) and He II (1640 Å) show pronounced variations. These are similar to line variations reported by Rucinski (1985) from a series of spectra taken of AB Dor. It is unclear, however, whether these variations are real or merely caused by noise or measurement error in these extremely noisy spectra. The error bars quoted are estimates of 1 σ confidence intervals based upon an analysis of the noise measured through the entire spectrum. It is well known, however, that the particle radiation background can be very inhomogeneous and can locally enhance a small region without evidence of a discrete particle 'hit'.

By comparing the co-added SWP spectrum of HD 197890 with that of AB Dor (Fig. 2), we see that all of the prominent lines agree in relative strengths, with the exception of the line near 1670 Å which is probably caused by O III or Al II. This line is also the most variable in our series of spectra, ranging from being undetectable (in SWP44383 and SWP44384) to being very pronounced (e.g. SWP44573 and SWP44391). In one case, there was an obvious particle event at this wavelength (SWP44392), but other spectra appear to be unaffected by this type of event.

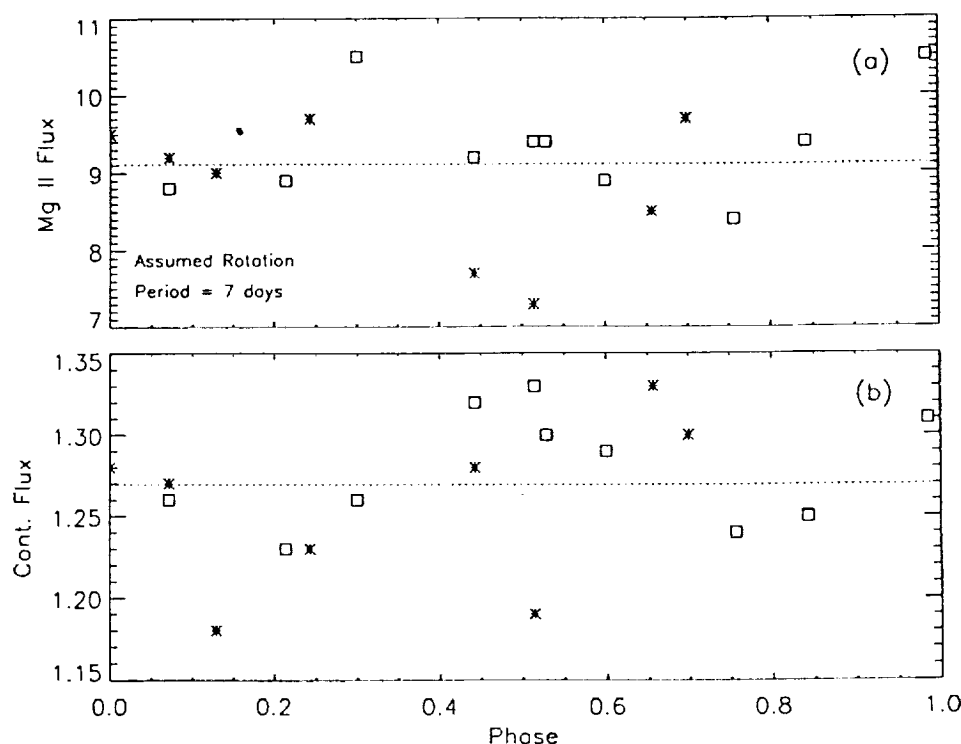


Figure 4. (a) Variations in the Mg II emission-line flux (in units of 10^{-13} erg cm $^{-2}$ s $^{-1}$), extracted from the spectrum as described in the text. The squares indicate measurements from the continuous LWP time sequence taken on April 14. The stars indicate measurements taken during the other three shifts. Phases were calculated using an arbitrary zero-point and a rotation period of 7 h. The dashed line indicates the average flux level. (b) Observed variations in the stellar flux integrated between 2700 and 2900 Å (in units of 10^{-11} erg cm $^{-2}$ s $^{-1}$), excluding the region between 2785 and 2815 Å, which contains the Mg II emission line. The symbols are the same as used in (a), while the dashed line again represents the average flux level.

Table 2. Near-UV fluxes.

Image	Exposure Number	Continuum ¹ Intensity ²	Mg II flux ³			Phase ⁴
			Gross	Net	Final	
LWP22781	1	1.28	12.5	7.8	9.5	0.00
LWP22781	2	1.27	12.5	7.4	9.2	0.07
LWP22782	1	1.28	10.8	6.1	7.7	0.44
LWP22782	2	1.27	10.6	5.6	7.3	0.51
LWP22793	1	1.30	12.8	8.0	9.7	0.70
LWP22794	1	1.23	12.7	8.0	9.7	0.24
LWP22803	1	1.18	12.1	7.4	9.0	0.13
LWP22804	1	1.33	11.9	6.6	8.5	0.66
LWP22811	1	1.30	12.9	7.6	9.4	0.53
LWP22811	2	1.29	12.2	7.2	8.9	0.60
LWP22812	1	1.24	11.7	6.6	8.4	0.76
LWP22812	2	1.25	12.6	7.6	9.4	0.84
LWP22813	1	1.31	13.8	8.7	10.5	0.99
LWP22813	2	1.26	11.9	7.1	8.8	0.07
LWP22814	1	1.23	11.9	7.2	8.9	0.21
LWP22814	2	1.26	13.7	8.7	10.5	0.30
LWP22815	1	1.32	12.8	7.2	9.2	0.44
LWP22815	2	1.33	12.8	7.5	9.4	0.51

¹Continuum integrated between 2600 and 3000 Å. ²Fluxes in units of 10^{-11} erg cm $^{-2}$ s $^{-1}$. ³Fluxes in units of 10^{-13} erg cm $^{-2}$ s $^{-1}$. ⁴As defined in Table 1.

The details of the radio measurements are presented in Table 4. The flux densities and positions were obtained by fitting an elliptical brightness distribution to each image. The observations, each lasting for 8 to 12 h, effectively covered

the rotation period of the star. Therefore, if there had been significant rotational modulation of the radio emission during each observation, one would expect to see pronounced asymmetry in the stellar radio image. There is, in fact, no evidence of image defects at the 10 per cent contour level. It is, however, clear from Table 4 that the flux density of HD 197890 increased by factors of 1.6 and 2.4, respectively, at 4.8 and 8.4 GHz between the March and April observations, and that the spectral index became much less negative. We know that these changes in flux density are genuine because the flux densities of sources B and C were constant to within 5 per cent on all three days. It is therefore clear that, although there were no large intensity changes over time-scales of hours to 2–3 d, significant alterations did occur over the three weeks between the first and last observations.

4 DISCUSSION

It now appears that HD 197890 is the most rapidly rotating nearby single, late-type dwarf star known, with a period comparable with the WUMa contact binary systems (Rucinski 1985). Numerous studies have shown that the degree of chromospheric and coronal activity on a star increases with decreasing rotation period (e.g. Noyes et al. 1984; Hartmann et al. 1984; Simon & Fekel 1987). This is generally thought of as a manifestation of the dynamo process in which differential rotation (assumed to be related

Table 3. Far-UV line fluxes.*

Peak Wavelength	ID	SWP Image Number						Mean Spectrum
		44372	44373	44383	44384	44391	44392	
1302	O I(2),S I	0.0±0.4	2.2±0.3	1.9±0.3	4.2±0.4	3.6±0.3	3.8±0.3	3.1±0.2
1335	C II(1)	7.4±0.4	7.3±0.4	3.8±0.3	6.6±0.4	7.1±0.3	9.8±0.4	7.1±0.2
1400	Si IV(1),O IV	1.6±0.5	2.7±0.5	1.4±0.4 [†]	3.5±0.4	4.9±0.4	3.1±0.4	3.1±0.2
1549	C IV(1)	16.5±0.4	15.5±0.4	12.8±0.3	14.5±0.3	15.4±0.4	15.5±0.3	15.0±0.2
1640	He II, Fe II(43)	3.5±0.4	7.2±0.4	8.8±0.3	8.1±0.3	4.6±0.4	9.7±0.3	6.9±0.2
1657	C I(2)	4.5±0.3	3.2±0.3	1.6±0.2	4.5±0.3	3.3±0.3	3.6±0.4	3.5±0.2
1666	O III,S I,Si I	2.3±0.3	5.0±0.3	0.0±0.3	0.8±0.4	3.2±0.3	9.0±0.3 [†]	3.0±0.2
1812	Si II(1),S I	4.1±0.5	5.4±0.5	2.4±0.4	6.2±0.4	6.0±0.4	4.6±0.3	4.9±0.3
1857	Al III(1),Fe II	1.3±0.3	0.3±0.3	0.6±0.2	0.4±0.3	2.5±0.2	0.0±0.3	0.7±0.2

* All fluxes are in units of 10^{-14} erg cm $^{-2}$ s $^{-1}$. † Fluxes influenced by particle hits.

Table 4. Radio measurements of HD 197890.

Date (1992)	Observing Interval (UT)	RMS Noise (μ Jy/beam)		Flux Density (mJy)		Power Output (10^{15} erg s $^{-1}$ Hz $^{-1}$)		Spectral Index†
		4.8 GHz	8.4 GHz	4.8 GHz	8.4 GHz	4.8 GHz	8.4 GHz	
March 19/20	16:48 to 00:41	81	115	1.28	0.57	2.4	1.08	-1.45 ± 0.17
April 10/11	15:05 to 03:40	116	148	2.10	1.41	4.0	2.68	-0.71 ± 0.17
April 12/13	15:24 to 03:36	111	159	1.93	1.29	3.67	2.45	-0.72 ± 0.17

† The error in the spectral index is computed from a 5 per cent uncertainty in the 4.8- and 8.4-GHz flux densities, based on the dispersion in the flux densities of sources B and C in Fig. 3.

to the rotational velocity itself) interacts with convective motions to generate magnetic fields. These fields then participate in non-radiative heating of the stellar atmosphere and account for the observed activity. At some level the process saturates, so that an increased rotation rate no longer results in an increase in the particular activity indicator (e.g. Vilhu & Walter 1987). One problem with the studies of activity saturation is the lack of single stars in the sample, so that most of the 'saturated' objects are members of rapidly rotating binary systems, many of which are in contact and strongly interacting with one another. The underlying assumption that such objects mimic a single, rapidly rotating star is far from obvious. Further, because of the limited number of active stars with known rotation periods, most studies relating activity and rotation have combined a large range of spectral types by using the Rossby number (i.e. the rotation period divided by the convective turn-over time) instead of the rotation period itself. Again, the validity of this assumption is open to question.

To investigate the chromospheric activity level on HD 197890 in more detail and determine its relation to similar types of stars, we searched the literature for single, main-sequence stars with known rotation periods and a spectral type near that of HD 197890, with a $B-V$ colour ranging from 0.75 to 1.0 (i.e. G8 to K2). From these, we chose stars with at least one well-exposed spectrum in the *IUE* archives. A total of 18 stars were selected, ranging in rotation periods from 12.6 h to 42 d. The list is presented in Table 5. The majority of these stars had two or more good-

quality *IUE* spectra available. In these cases, the spectra were co-added using a weighted-mean technique similar to that described in Section 2. This not only improved the signal-to-noise ratio, but helped to average out variations caused by activity cycles.

In this paper we will concentrate on the Mg II h and k lines near 2800 Å and the C IV lines near 1550 Å, common indicators of chromospheric and transition region activity, respectively. These fluxes were extracted from the *IUE* spectra using the same techniques as used for the HD 197890 data (see Section 2), and the results are presented in Table 5. Comparison of our results with published fluxes shows a close agreement in most cases. A common way of comparing stars is to divide the measured integrated line flux by the bolometric flux, defined (e.g. Vilhu & Rucinski 1983) as

$$f_{\text{bol}} = 2.7 \times 10^{-5} \times 10^{-0.4(m_V + BC)} \text{ erg cm}^{-2} \text{ s}^{-1}.$$

The bolometric correction (BC) was determined from the $B-V$ colours using the relation tabulated by Popper (1980). The results are presented in Table 5 and plotted in Figs 5 and 6. The Mg II flux shown in Fig. 5(a) has a simple log-linear relation for the most rapidly rotating stars (period < 6 d), with no indication of a saturation. A linear regression to these more rapidly rotating stars gives the expression

$$\log_{10} R_{\text{hk}} = -4.046 - 0.339 \log_{10} P,$$

Table 5. Data for period-activity relation.

HD Number	V	B-V	τ_C (days)	B.C.	F_{bol}^*	Period (days)	P/τ_C	F_{hk}^\dagger	$\log(F_{hk}/F_{bol})$	F_{CIV}^\dagger	$\log(F_{CIV}/F_{bol})$
17925	6.0	0.87	21.3	-0.29	14.00	6.60	0.31	65.0±3.0	-4.33±0.05	3.0±0.6	-5.67±0.13
22049	3.73	0.88	21.5	-0.29	113.6	11.3	0.53	558±23.	-4.31±0.06	8.1±0.5	-6.15±0.07
26354	8.6	1.00	23.0	-0.44	1.47	2.6	0.11	—	—	1.7±0.8	-4.95±0.22
36705	6.8	0.82	20.0	-0.25	6.48	0.53	0.025	73.0±4.0	-3.95±0.07	11.9±0.3	-4.74±0.06
71071	7.9	0.95	22.5	-0.38	2.65	16.5	0.73	—	—	0.2±0.2	-6.12±0.35
82558	7.8	0.92	22.2	-0.34	2.80	1.60	0.07	20.8±2.0	-4.13±0.07	3.6±0.4	-4.89±0.08
82885	5.4	0.78	18.6	-0.21	22.67	18.10	0.97	67.5±3.0	-4.53±0.06	0.8±0.3	-6.45±0.18
101501	5.3	0.72	15.9	-0.17	23.95	17.10	1.07	—	—	2.0±0.7	-6.08±0.17
115404	6.5	0.93	22.3	-0.35	9.36	18.80	0.84	43.5±2.0	-4.33±0.05	—	—
131156A	4.54	0.77	18.2	-0.21	50.0	6.2	0.34	256±30	-4.29±0.10	6.4±0.5	-5.89±0.09
149661	5.74	0.81	19.7	-0.24	17.0	21.3	1.08	56.3±3.0	-4.48±0.06	0.64±0.2	-6.42±0.14
152391	6.6	0.75	17.3	-0.19	7.37	11.10	0.64	37.4±1.5	-4.29±0.05	—	—
155885	5.3	0.77	18.2	-0.20	24.62	20.30	1.12	—	—	2.6±0.5	-5.98±0.12
160346	6.5	0.96	22.6	-0.39	9.71	33.50	1.48	21.0±7.0	-4.66±0.16	0.2±0.1	-6.69±0.22
165341A	4.03	0.86	21.1	-0.28	85.4	19.7	0.93	348±20	-4.39±0.06	—	—
166620	6.4	0.87	21.3	-0.29	9.4	42.0	1.97	9.8±0.8	-4.98±0.06	—	—
174429	7.8	0.79	19.0	-0.22	2.51	0.94	0.05	21.5±0.5	-4.07±0.06	1.8±0.3	-5.14±0.10
175742	8.1	0.90	21.9	-0.32	2.09	2.90	0.13	—	—	2.1±0.3	-5.00±0.10
197890	9.3	?	20.0	-0.25	0.65	0.29	0.015	9.4±1.3	-3.84±0.09	1.6±0.2	-4.61±0.09

* Units of 10^{-8} erg cm $^{-2}$ s $^{-1}$. †Units of 10^{-13} erg cm $^{-2}$ s $^{-1}$.

where P is the rotation period in days. Note the pronounced departure from this simple relation for the more slowly rotating stars. The most obvious effect is an apparent enhancement of the expected Mg II flux shown by four of the stars having periods between 8 and 20 d. Each of these stars had two or more spectra (thereby eliminating some of the activity cycle effects) and the departures were greater than the expected error in the measurement. The apparent rapid fall-off of flux from that expected for periods greater than 20 d is primarily dependent upon the slowly rotating star HD 166620 (period = 42 d) and should be checked with observations of other slowly rotating objects.

Some of the scatter in Fig. 5(a) may be caused by the range of spectral types of the stars used in the study. A common method for removing the temperature dependence in period-activity studies is to plot the activity indicator against the Rossby number, defined as the rotation period divided by the convective turnover time, τ_C . This has been done in Fig. 5(b), where τ_C is determined from the relation given by Noyes et al. (1984) and we have assumed a $B-V$ for HD 197890 equal to that of AB Dor. The scatter is improved somewhat but the overall results are unchanged. Note that if HD 197890 were cooler than AB Dor, as suggested by Anders et al. (1993), then τ_C would be slightly larger than the assumed value and the agreement with the fitted relation would be improved. Fig. 5(b) also indicates the expected Mg II 'saturation' level for early K stars ($B-V=0.85$), as presented by Vilhu & Walter (1987). This indicates that even the most active stars in the sample are still far from saturated in Mg II.

The C IV observations (Fig. 6) show a simple power-law relation for the slowly rotating stars, with a scatter consistent with measurement errors and activity cycle variations. In contrast to the Mg II results, the C IV flux appears to saturate on stars with periods less than 2 d, in that the rate of increase

in C IV flux with decreasing rotation period abruptly decreases at that point. A least-squares fit to the data gives

$$\log_{10} R_{CIV} = -4.82 - 0.357 \log_{10} P; \text{period} < 2 \text{ d}$$

$$\log_{10} R_{CIV} = -4.52 - 1.378 \log_{10} P; \text{period} > 2 \text{ d}.$$

The relation for the rapidly rotating stars is close to that presented by Simon & Fekel (1987) for their group of active chromosphere dwarfs, which include binary systems and single stars covering a wide range of spectral types. Fig. 6(b) also shows that the level of C IV flux in HD 197890 is near the absolute saturation value measured by Vilhu & Walter (1987).

From Fig. 6(b) we see that the C IV saturation first occurs at a Rossby number of 0.1. This is near the critical Rossby number identified by Knobloch, Rosner & Weiss (1981) at which the convective cells change rapidly from the normal convective pattern to convection in rolls parallel to the rotation axis. The saturation may thus be related to the effect that these changing convective motions have on the generation of magnetic fields. Another possibility is that saturation relates to the structure of the magnetic fields and/or changes in the non-radiative heating mechanism with increasing concentration of surface fields. In this context it is interesting to note that, whereas the Mg II fluxes did not saturate at even the lowest Rossby numbers, the X-ray flux shows a saturation at Rossby numbers as large as 0.7 (Vilhu 1984). This suggests an increased tendency to saturate with an increase in the temperature of the emitting plasma.

Finally, we note that, with the exception of PZ Tel (HD 174429), the rapidly rotating stars show very little scatter about the fitted curve. This deviation of the C IV flux for PZ Tel is difficult to explain. The difference is much larger than the measurement errors (a factor of 2 from the expected flux) and the measured fluxes were nearly identical

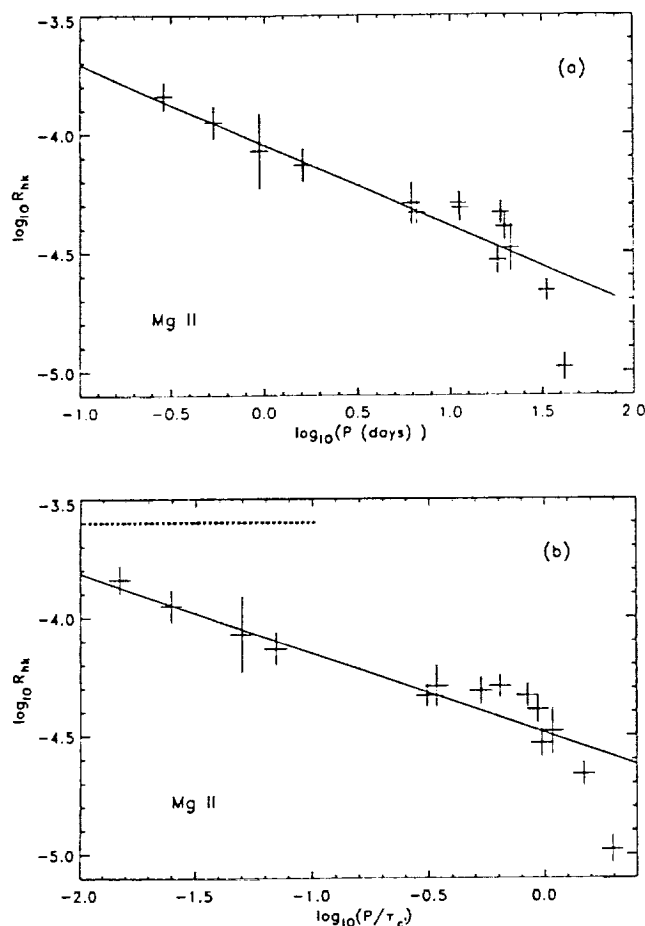


Figure 5. (a) Comparison of the Mg II activity index (R_{hk}) with the rotation period of the star. R_{hk} is defined as the integrated Mg II h and k emission-line flux divided by the bolometric flux of the star. The error bars are 3σ estimates which include the effects of instrumental noise, extraction uncertainties and uncertainties in the bolometric flux. (b) As above, except that the Mg II flux index is plotted against the Rossby number, defined as the rotation period (P) divided by the convective turn-over time (τ_c). The values of τ_c were derived from the relation given in Noyes et al. (1984). The dotted line shows the saturation level for this class of star as deduced by Vilhu & Walter (1987).

in the two available SWP spectra of this star, which were taken a year apart. PZ Tel is thought to be a member of the Local Association (Innis et al. 1986), and has properties very similar to those of other members of this group. Note, for example, that the Mg II flux for PZ Tel is consistent with those of the other rapidly rotating stars (Fig. 5). Obviously, more study will be needed to resolve this discrepancy.

Turning now to the radio data, we find that the emitted radio flux ranges from 1.08 to $2.68 \times 10^{15} \text{ erg s}^{-1} \text{ Hz}^{-1}$ at 8.4 GHz (3.6 cm), and from 2.4 to $4.0 \times 10^{15} \text{ erg s}^{-1} \text{ Hz}^{-1}$ at 4.8 GHz (6 cm), assuming a distance of 40 pc to the star (Bromage et al. 1992). The only other radio data on this star have been obtained with the VLA by Brown et al. (1994), who report a mean integrated flux of $1.66 \times 10^{15} \text{ erg s}^{-1} \text{ Hz}^{-1}$ at 8.4 GHz on 1992 February 22, in general agreement with our results. Brown et al. (1993) also show a small variation in the flux levels, with a maximum amplitude of about 20

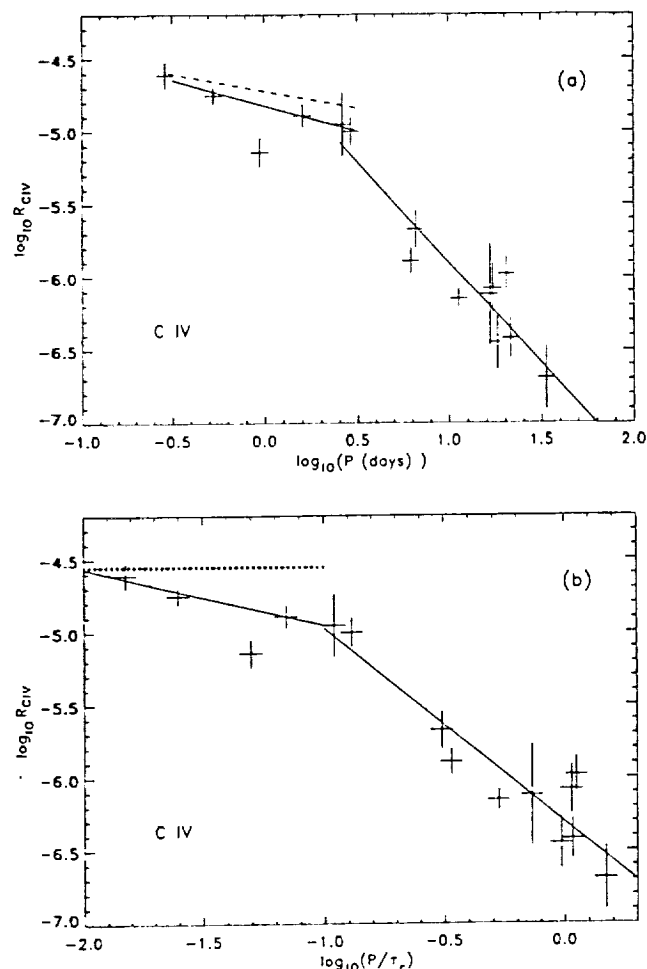


Figure 6. (a) Comparison of the C IV activity index (R_{CIV}) with the rotation period. R_{CIV} is defined as the integrated C IV flux divided by the bolometric flux of the star. The error bars and symbols are as in Fig. 5. (b) Comparison of R_{CIV} with the Rossby number, as in Fig. 5 (b). The dotted line indicates the saturation level for the C IV flux as deduced by Vilhu & Walter (1987).

per cent, which might have resulted from rotational modulation or small flaring events. Overall, the flux changes seem to occur on very long time-scales, and we take our measured averages as representative of the general flux level outside major flare events. These fluxes are consistent with the overall trend relating 8.4-GHz flux to rotation rate in K dwarfs, as reported by Gudel (1992), and are also consistent with the *minimum* levels found in other rapidly rotating stars such as AB Dor (HD 36705) and PZ Tel (HD 174429). For example, AB Dor, with a rotation period of 12 h and a distance of 25 pc (Rucinski 1985), has minimum fluxes near $1.9 \times 10^{15} \text{ erg s}^{-1} \text{ Hz}^{-1}$ at 8.4 GHz (Gudel 1992) and $2.2 \times 10^{15} \text{ erg s}^{-1} \text{ Hz}^{-1}$ at 4.8 GHz (Lim et al. 1992). However, despite the relatively high level of quiescent activity, HD 197890 shows no evidence for the strong flux variations that characterize AB Dor and other rapidly rotating stars (e.g. Slee et al. 1987a). Lim et al. (1992), for example, found a strong, double-peaked rotational modulation on AB Dor which varied from a minimum of 3 mJy to values in excess of

15 mJy at 4.8 GHz. The radio flux varied in phase with starspot visibility, and Lim et al. interpreted the observations as evidence for enhanced radio emission over active regions. This study confirms the suggestions of rotational modulation made by Slee et al. (1986), who reported 8.4-GHz fluxes in excess of 70 mJy during a programme covering several months of intermittent observing. However, despite more than 35 h of on-source observing, covering all rotational phases and spanning more than two months, the radio flux from HD 197890 did not exceed 2.1 mJy at either 4.8 GHz or 8.4 GHz.

It is clear from the errors assigned to the spectral indices in Table 4 that there was a significant reduction in the slope of the microwave spectrum between the observations of 1992 March and 1992 April. Brown et al. (1993) report average 8.4-GHz fluxes of 1.07 mJy (intermediate between the fluxes obtained in our observations), but find a spectral index between 4.8 and 8.4 GHz of 0.38, which is much lower than our values. Considerable care must be taken in this comparison, however, because the 4.8- and 8.4-GHz measurements of Brown et al. were taken sequentially, in contrast to our simultaneous observations at the two frequencies.

Probably the most relevant comparison is with the spectral changes seen in the apparently similar star AB Dor by Slee et al. (1987b). In AB Dor, the spectral index between 2.9 and 8.4 GHz varied between slightly negative and slightly positive at times of elevated activity. This scenario is consistent with a radio source in which the optical thickness increases with emitted power, with the optically thin part of the spectrum shifting to higher frequencies. It will not be possible to model the radio source adequately until we have a detailed radio spectrum and measurements of circular polarization.

5 CONCLUSIONS

We report UV and radio observations of the rapidly rotating K dwarf star HD 197890. UV emission lines were found to be extremely intense in this object. After dividing by the bolometric luminosity to remove distance effects, these lines were found to be stronger than those of any other K dwarf known, and comparable in strength to those of other active stars such as W UMa contact binaries, RS CVn binaries and dMe flare stars. Comparison of the UV and minimum radio activity level on HD 197890 with those of stars of similar spectral type but different rotation rate shows that the average activity level on HD 197890 is consistent with the trends established by the more slowly rotating stars.

A search for rotational modulation in the UV and radio flux, which might be related to the observed starspot activity, gave generally negative results. While a weak rotational modulation appears in the UV continuum, no detectable short-term variations were seen at radio wavelengths and only scattered fluctuations in the integrated Mg II flux were detected. These variations were much larger than the

expected instrumental effects, and probably result from weak transient activity. There was no evidence for an extreme outburst such as that observed by *ROSAT*.

It is perhaps not surprising that, despite the star's very high rotation rate, we have not yet detected the much higher flux densities that have been recorded from similar stars such as AB Dor and PZ Tel. The flare activity on these stars can remain at very low levels for several days in succession, so that infrequent sampling of the star's flux density (such as we have conducted on HD 197890 up to now) is not likely to lead to valid conclusions about its highest activity levels. However, if continued monitoring shows that the star persists in its low levels of activity, it would provide evidence for a dramatic change in the characteristics of the magnetic field dynamics and perhaps of the dynamo itself at extreme rotation rates.

REFERENCES

- Anders G. J., Jeffries R. D., Kellett B. J., Coates D. W., 1993, *MNRAS*, 265, 941
 Ayres T. R., Judge P. G., Jordan C., Brown A., Linsky J. L., 1986, *ApJ*, 311, 947
 Bromage G. E., Kellett B. J., Jeffries R. D., Innis J. L., Matthews L., Anders G. J., Coates D. W., 1992, in Giampapa M. S., Bookbinder, J. A., eds. *ASP Conf. Ser. Vol. 26, Cool Stars, Stellar Systems and the Sun, Seventh Cambridge Workshop*. Astron. Soc. Pac., San Francisco, p. 80
 Brown A., Bromage G. E., Ambruster C. W., Jeffries R. D., 1994, *ApJ*, submitted
 Collier Cameron A., Robinson, R. D., 1989, *MNRAS*, 236, 57
 Duncan D. K., 1981, *ApJ*, 248, 651
 Gudel M., 1992, *A&A*, 264, L31
 Hartmann L., Baliunas S. L., Duncan D. K., Noyes R. W., 1984, *ApJ*, 279, 778
 Innis J. L., Thompson K., Coates D. W., 1986, *MNRAS*, 223, 183
 Jeffries R. D., 1993, *MNRAS*, 262, 369
 Knobloch E., Rosner R., Weiss N. O., 1981, *MNRAS*, 197, 45
 Lim J., Nelson G. J., Castro C., Kilkenny D., Van Wyk F., 1992, *ApJ*, 388, L27
 Noyes R. W., Hartmann L. W., Baliunas S. L., Duncan D. K., Vaughan A. H., 1984, *ApJ*, 279, 763
 Parker E. N., 1979, *Cosmical Magnetic Fields. Their Origin and their Activity*. Clarendon Press, Oxford
 Popper D. M., 1988, *ARA&A*, 18, 115
 Rucinski S. M., 1985, *MNRAS*, 215, 615
 Simon T., Fekel F. C., Jr, 1987, *ApJ*, 316, 434
 Slee O. B., Nelson G. J., Innis J. L., Stewart R. T., Vaughan A. E., Wright A. E., 1986, *Proc. Astron. Soc. Aust.*, 6, 312
 Slee O. B., Nelson G. J., Stewart R. T., Wright A. E., Innis J. L., Ryan S. G., Vaughan A. E., 1987a, *MNRAS*, 229, 659
 Slee O. B. et al., 1987b, *Proc. Astron. Soc. Aust.*, 7, 55
 Stauffer J. R., 1991, in Catalano S., Stauffer J. R., eds, *Angular Momentum Evolution of Young Stars*. Kluwer, Dordrecht, p. 117
 Vilhu O., 1984, *A&A*, 133, 117
 Vilhu O., Rucinski S. M., 1983, *A&A*, 127, 25
 Vilhu O., Walter F. M., 1987, *ApJ*, 321, 958